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# Perspectives of double skin façade systems in buildings and energy saving

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ABSTRACT

One of the most important methods of saving energy in a building is by carefully designing its facade. A 'double skin façade' is optimally one of the best options in managing the interaction between the outdoors and the internal spaces. It also provides some architectural flexibility to the design. Recently it has received much attention as opposed to the more typically glazed curtain wall. This is because of its ability to efficiently reduce energy and therefore saves cost. The amount of energy saved depends on the climate and the design chosen. The design of the DSF involves decisions on geometric parameters, glass selection, ventilation strategy, shading, daylighting, aesthetics, wind loads, and maintenance and cleaning cost expectations. DSF has an impact on several aspects of the design phase of a building. For example, thermal properties, acoustic characteristics and daylighting are affected in the exploitation phase of the building. In addition, in terms of building safety point of view, fire propagation maintenance or glazing thermal break must be taken into account. Currently, little work has been done on the behaviour of DSFs in hot and humid climates. This paper shall review previous studies made on double skin façade systems (DSFS) in buildings.



**Contents**



## 1. Introduction

Conventional building skin facades are known to have numerous problems such as thermal comfort, natural ventilation and glare especially in buildings with high glazing skin, which are located in hot temperature regions. These problems encourage the engineers to sought ways of and improving the problems faced by the utilisation of new techniques and devices such as shading devices, colour glass and tint glass. The adoption of these techniques have shown a reduction in natural lighting, and the increase in the use of artificial light; which inevitably led to the increase in the interior heat gain besides the utilisation of other electric devices and office equip-

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ments that were used to counter the lack of penetration of external illumination. This interior heat gained is coupled with the external heat gained coming from solar radiation that is usually caused in some cases by poorly shaded buildings. To combat this situation, air-conditioning is used to cool down the heat effect. This results in the increase of energy consumption which leads to the increase the cost [1,2].

In 1990s, the concern pertaining to global warming and of the increasing demand for high-quality office building encourages the engineers and developers (who are interested in natural cooling strategies) to look for new techniques as solutions, together with clear and environmental friendly energy to be used as an alternative source of energy for artificial lighting for buildings, ventilation and air-conditions [3].

Double skin facade—DFS are used to better the thermal energy performance of facades of buildings with high glazing fractions. It is made of an external glazing offset from an internal glazing integrated into a curtain wall. It commonly features a controllable shading system located in the cavity between the two glazing systems [3,4]. It has gained much popularity in prevalent time for its ability to reduce solar heat gain or losses in buildings [5–7]. In fact, it has become highly significant worldwide modern building practice especially in cool climate regions. The main architectural reason for using DSF is in its transparency properties because it allows close contact with the surroundings of the building, and of the fact that it admits a large amount of daylight to enter the building without glare. Finally it has attractive aesthetic value which is much desired by architects, developers and owners [8,9]. On the other hand, there are several disadvantages of using DFS; one of them is the investment cost that is considerably much higher than a traditional single-facade. Furthermore, the risk of overheating on warm sunny days is evident and may lead to a higher cooling demand [10,11]. The design of the DSF involves decisions on geometric parameters glass selection, ventilation strategy, shading, daylighting, aesthetics, wind loads, and maintenance and cleaning cost expectations [12].

Unfortunately, to date, there are still relatively few buildings which actually use DSF. Furthermore, there is too little information on their operational behaviour. Thus it is said that it is quite difficult to find any objective data on the actual performance of buildings with DSF (1, 10 and 11). In this paper we will discuss some of the configuration issues in designing a DSF, where the aims of this study is to give a broad overview of double skin façade for different climate and regions.

## 2. An overview of the previous studies

Previous studies on DSF for various purposes can be grouped by at least nine main titles. They can be listed as follows: ventilation, daylighting, performance and effect, simulation models and experiments, shading devices, solar photovoltaic, glass selection, smoke, and cavity depth.

### 2.1. Definition of double skin façade system

There are various definitions of the DSF System.
According to Safer et al. 2005 [13]:

"Double-skin facade is a special type of envelope, where a second skin, usually a transparent glazing, is placed in front of a regular building facade. The air space in between, called the channel, can be rather important (up to 0.8–1.0 m). In general the channel is ventilated (naturally, mechanically, or using a hybrid system) in order to diminish overheating problems in summer and to contribute to energy savings in winter".

Ding et al. 2005 [11] stated that:

"Double-skin facade is composed of an external facade, an intermediate space and an inner facade. The outer facade layer (glazing) provides protection against the weather and improved acoustic insulation against external noise. An adjustable sunshade device, such as blinds, is usually installed in the intermediate space to protect the internal rooms from high cooling loads caused by insulation"

Roth et al. 2007 [14], Baldinelli 2009 [15] stated that;

"Compared to a single-skin facade, a DSF consists of an external glazing offset from an internal glazing integrated into a curtain wall, often with a controllable shading system located in the cavity between the two glazing systems. Typically, the external glaring is a single layer of heat-strengthened safety or laminated safety glass, while the interior layer consists of single- or double-pane glass with or without operable windows".

Kim and Song 2007 [16], Wang 2008 [1] espoused that:

"Double-skin facades are multiple layer skins construction with an external skin, an intermediate space and an inner skin. The external and internal skins could be of either single glaze or double glazed glass panes of float glass or safety glass. An adjustable sun shading device is usually installed at the intermediate space for thermal controls. The double-skin constructions generally could be grouped under Box Window facade, Shaft-box facade, Corridor facade and Multi-story façade".

Chan et al. 2009 [2] contended that:

"Double skin facade refers to a building facade covering one or several stories with multiple glazed skins. The skins can be air tight or naturally/mechanically ventilated. The outer skin is usually a hardened single glazing and can be fully glazed. Inner skin can be insulating double glazing and is not completely glazed in most applications. The width of the air cavity between the two skins can range from 200 mm to more than 2 m. An air-tightened double skin facade can provide increased thermal insulation for the building so as to reduce the heat loss in winter season. On the other hand, moving cavity air inside a ventilated double skin facade can absorb heat energy from the sun-lit glazing and reduce the heat gain as well as the cooling demand of a building".

## 3. Important aspects of DSF

### 3.1. DSF ventilation

Ventilation is used for different purposes. Its principal purpose is to exchange contaminated air with clean air. It is also important to create a room climate without draught problems and only slight temperature changes in the occupied zone [17]. DSF is categorized according to its function (i.e. ventilation type of the cavity). They are the natural, the mechanical and the hybrid ventilation. In order to provide fresh air before and during the working hours, different types of DFS ventilation can be applied in different climates, orientations, locations and building types to minimize the energy consumption and improve the comfort of the occupants [18].

Gratia and Herde 2004 a, b and c [10,19,20] evaluated the natural ventilation of the double-skin facades that is influenced by both buoyancy and wind force. This involved the natural ventilation in DSF with TAS software. They also discussed sensitive factors that affect building facades such as wind direction, and building orientation. In addition, it is found that natural ventilation and smoke control can be achieved through a single system.

Furthermore, Ding et al. 2005 [11] suggested adding a thermal storage space called a solar chimney above the double-skin

space to improve the stack effect in the double skin. Reduced-scale-model experiments and computational fluid-dynamic analyses were carried out to evaluate the performance of the natural ventilation in prototype building. Suffice to say, the system improved the chimney effect of the double skin despite necessitating a chimney reaching at least 11 meters above the building. However, this is no doubt a significant aesthetic constraint.

In addition, Ballestini et al. 2005 [7] analysed and investigated the possibility of applying passive solar systems in a Mediterranean climate. This analysis took place in a silk factory. The study was made with reference to a double-skin facade and natural ventilation. In particular, it involved dynamic simulations that were performed by TRNSYS and LOOPDA simulation models. It is demonstrated how natural ventilation can be obtained by means of internal airflow paths running through the whole buildings height between floors. The results showed that DSF can be a valuable solution for building renovation; it may save up to 12% of energy consumption.

Moreover, Ding and Hasemi. 2006 [21] used Reduced-scale model experiments and Computational Fluid Dynamics (CFD) analysis to test the double-skin façade for natural ventilation as well as for smoke control. As a result, it was proven that smoke spread can be prevented with suitable opening arrangements. However, there were no detailed analyses on the natural ventilation in the double skin facade with Venetian blind.

Further researches and studies on DSF were also done by Gartia and Herde 2007c [22] who examined how natural ventilation can be achieved during a sunny summer day in an office building with a double-skin façade (DSF). They concentrated on the possibility of natural ventilation during the daytime in relation to the orientation of the double skin and the speed and orientation of the wind. It determined the way in which the DSF should be opened, and the size of the openings necessary, to achieve a ventilation rate of 4 ach in each office under various wind conditions. However, these results cannot be generalised to other configurations of DSF, and are insufficient for the technical design of a double skin facade as it is only the initial step towards a better understanding efficient DSF design.

Ensuing with the findings by Gartia and Herde 2007c, the researchers of this study brings to attention the study done by Kim and Song 2007 [16] who examined the contribution of a Double Skin Envelope (DSE) to the heating energy savings brought by natural ventilation in office buildings. A DSE was applied to the east and west facing walls on an actual three-floor building. Field measurements and computer simulations were performed in winter. The results implied that the DSE on the west-facing wall contributed to energy savings when natural ventilation was supplied from the cavity to the indoor space. The DSE facing east was not recommended for energy savings by natural ventilation because of its smaller exposure to solar irradiance.

Other related studies include a study done by Manz et al. 2004 [23] who implemented numerical simulations on the natural and mechanical ventilation for glass double facades (GDFs). It was found that airflow patterns depend on boundary conditions and it is much more complex than postulated by the piston-flow assumption in simple analytical models finally, it demonstrated that a change in the orientation of the facade flow can influence the total solar energy gain.

In addition, for numerical simulation Lu et al. 2005 [24] studied ventilation in DSF by using computational fluid dynamics (CFD) modelling and wind tunnel test. It was shown that the Subgrid-scale (SGS) model of large eddy simulation correctly predicted wind field in this case. Multi obliquity and different approaching flows models were utilized to investigate the effects of shutter obliquity on ventilation. Shutters were shown to have an air-oriented effect to certain extend, and the optimal obliquity is near 45° in all different wind directions.

In another study done by Balocco 2004 [6], he defined 14 dimensionless variables to describe thermal and energy performance of different facade designs, whereas in another similar study by Balocco and Colombari 2006 [25], they defined 12 dimensionless variables that can be used to describe thermal and energy performance of different façade design.

In addition, Xu and Yang 2008 [26] made a detailed analysis of the thermal process in glass double facade with Venetian blind. Governing equations were solved by using CFD, optical and heat balance model for multi-layered transparent system. It was found that the more complex natural ventilation exists in the two air gaps divided by the Venetian blind, which cannot be reflected with the simplified model. It can be used as a reliable tool to analyse the ventilation in the double skin facade with Ventilation blind. The results show that there is good agreement achieved between the simulation and experimental results for the maximal and minimal errors, which are 12% and 2.5% respectively. The reliability of the simulation model is thus verified.

Double-skin facades (DSF) are a technique developed for colder climates, so few people think about whether or not it can also be used for hot-summer. Zhou et al. 2009 [27] studied it for hot summer and cold-winter zone in china. It was found that the ventilated DSF with controlled shading devices can be used even in hot summer in China.

### 3.2. Daylighting and DSF

The treatment of the light affects the experience of space and inner biological and psychological clock of humans. As such, natural daylight as a positive effect on humans has always been one of the main aspects considered in architectural design [28].

Viljoen et al. 1997 [29] investigated the possibility of improving day lighting for double skinned office buildings. Scale models were used in an artificial sky and computer simulations. This was to examine the effects of changes in re-entrant slots in the facade and lowering of the central area of the floor. The result showed that the daylight area can increase by up to 23% when it uses a walkway or cavity option alone, as compared to re-entrant facade slots that produced no increase in the daylight area. Lowering the central floor area produced an increase of up to 14% of light. None of the walkway options were able to produce a daylight area of greater than 53% of the total floor space.

In addition, Hien et al. 2005 [30], Gratia and Herde 2007a [5] espoused that using DSF can reduce the lighting energy consumption by making full use of day lighting. Furthermore, in another related study, Kim et al. 2007 [31] had also evaluated the control performance of a daylight dimming system by using double skin envelop (DSE) configurations under a variety of daylight conditions. The purpose was to propose a better control alternative in a small office space. Computer simulations were performed for photosensors positioned at three different locations in three different shielding conditions with three different sky conditions. The result showed that a partially shielded condition generally achieved good dimming performance under clear and intermediate cloudy skies.

On the other hand, Hoseggen et al. 2008 [32] claimed that the additional glass layer reduces the indoor daylight illumination levels. According to Poirazis 2005 [17] the daylight properties of DSF are similar to other types of glazed facades (i.e. single skin façade). This means that an area of the floor space is considered to be daylight when it receives at least 300 Lux for over 50% of the working year. Based on the previous mentioned studies, they demonstrated a lack of deep details pertaining to the performance of DSF and the results did not show how the structure of the building and its cavity should be constructed to obtain the optimal performance of light-

ing in DSF. These studies discussed the light performance in general and unfortunately no adequate studies or researches were carried out regarding this topic.

### 3.3. Performance and effect of DSF

In discussing the performance and effect of DSF, Yoon et al. 1997 [33] evaluates the effects of a south-facing double-skinned facade and a ground-coupled heat exchanger on the annual energy performance of a three story experimental office building. The results show that the energy saving due to the double-skin and the ground-coupled heat exchanger is about 12–23%. Also during the heating season, the double-skin is more effective than the ground-coupled heat exchanger in terms of reducing the heating demand.

Pasquay 2004 [18] wrote a report regarding the thermal performance of three buildings with double skin façade (DSF). They are the Siemens building, the Victoria Insurance Company and the RWE Tower. It was shown that the indoor temperature was slightly affected by the outdoor weather. In addition, faulty double-skin facade could generate catastrophic scenarios such as the injection of hot air from the double skin into the offices. In addition, the condition of air on one level can contaminate or affect the air on another level.

In a study done by Hien et al. 2005 [30], they investigated the effects of DSF with ventilation system on the energy consumption by using TAS and CFD software to calculate energy consumption, thermal comfort and condensation. The simulation result showed that DSF with natural ventilation were able to minimise energy consumption as well as enhance the thermal comfort.

Furthermore, in another study done by Yilmaz and Cetintas 2005 [34], they analysed heat losses of single and double skin façade office building to show the effect of DSF on building energy demand for winter period in Istanbul. It has been assumed that the space between the two skins is close since the conclusion has been made. They then developed a new method for DSF thermal evaluation. The result shows that heating energy consumption is significantly reduced in DSF building for winter conditions in Istanbul.

To tests the energy performance of DSF Pappas and Reilly 2006 [35] was using DOE 2.2 and energy plus software with DSF modelling. It found that DOE-2.2 predicts less than 1% annual cooling energy savings and 3% heating energy savings comparing the double skin façade to a conventional air distribution system. Energy Plus predicts a 3% reduction in the cooling and heating loads with the double skin façade as compared to a triple-glazed façade with no air flow between the glazings.

Charron et al. 2006 [36] presented theoretical investigation of the performance of double façade with integrated Photovoltaic (PV) and motorised blinds. They examined two configurations of the facade with lower section that were integrated with PV and an upper vision section with motorised blinds. The result showed that placing the blind in the middle of the cavity increases the vision section efficiency by 5%. In addition, it was found that using this approach to optimize performance can lead to a combined thermal-electric efficiency of over 60%.

Another great characteristic of the double-skin facade is the greenhouse effect. Gratia and Herde 2007b [8] studied the effect of greenhouse effect in DSF. They analysed the impact of parameters on the air temperature evolution in the cavity. The result shows that greenhouse effect is achieved if DSF is oriented to the south. However, there is no greenhouse effect if the DSF is in the north, east or west.

Pappas and Zhai 2008 [37] investigated the energy performance and possible factors that affects DSF. They developed an iterative modelling process with integrated CFD and building energy simulation program (BESP) to analyse the thermal performance of DSF. This was done using buoyancy-driven airflow. The result of modelling process was used to develop correlation for cavity airflow rate, air temperature stratification, and interior convection coefficient that can provide a more accurate energy analysis of a DSF with buoyancy-driven airflow within an annual building energy simulation program than is currently possible.

Chan et al. 2009 [2] reported the findings on the energy performance of DSF applied to a typical office building under Hong Kong climate condition. The energy-plus simulation was used to develop theoretical model. This model was used to evaluate the energy performance of DSF with various configurations. The result indicated that a DSF system with a single clear glazing as the inner pane and double reflective glazing as the outer pane can provide an annual saving of around 26% in the cooling energy of the building. This amount of energy saving is not found in conventional single façade with single absorptive glazing.

Chou et al. 2009 [38] presented a systematic method for investigating the effectiveness of DSF in reducing solar heat gain. They conducted several experiments to obtain the Solar Heat Gain Coefficient (SHGC) values of DSF fenestration system. The result showed that a building with DSF having a window wall ratio WWR of 0.3 reduces appreciable envelope thermal transfer value (ETTV) of up to 45%.

### 3.4. Simulation, modelling and experiments of DSF

Computer modelling and simulation are currently some of the most powerful techniques available to engineers and designers. Experimental and numerical models were used for studying the DSF. Models that were used for predicting and analysing DSF include analytical and lumped models, dimensional analysis, network models, control-volume models and Computational Fluid Dynamics (CFD). Lumped model was used for naturally ventilated DSF.

Zollner et al. 2002 [39] had proposed an investigation of the time and local averaged overall heat transfer coefficients for turbulent mixed convection fluid flow in transparent vertical channel.

Grabe [2002] [40] developed a simulation algorithm for temperature and flow characteristics of double facade to assist energy consultant to make quick decision without using CFD tools.

Park et al. 2004a, b [41,42] used lumped model which is calibrated on in situ measurements. It was found that the calibrated model was surprisingly accurate and is ideal for studying optimal control and performance.

Dimensional analysis was used to describe the energy performance of different DSF designs. Balco 2004 [6] proposed a non-dimensional analysis involving energy and thermal properties for a natural ventilated double facade. The non-dimensional analysis results were validated with experimental and CFD simulation results. The method can be applied to all natural ventilated facade typology.

In addition, airflow network models coupled with energy simulation were used to evaluate the natural ventilation of office buildings with DSF. Gratia and Herde 2004a [10] examined the efficiency of the natural day ventilation in relation to the double-skin orientation and the speed and orientation of wind.

In another related study, Gratia and Herde 2004c [20] compared the thermal behaviours of the building between double glazed facade and single glazed facade by using TAS software. They recommended operating the double glazed facade according to the climatic conditions.

Furthermore, Stec and Paassen 2005 [43] compared the performance of nine different facade systems for Dutch climate and concluded that the double skin systems were competitive in energy performance. They also stressed on the importance of treating the double-skin as an integrated part of the HVAC system. Moreover,

they emphasised on evaluating the energy performance of office buildings with DSF.

Some other researchers used the Computational Fluid Dynamics (CFD) approach to assess detailed characteristics of facade behaviour using the finite element method.

Manz 2004 [44] used a spectral optical model and a computational fluid dynamic model to simulate the total solar energy transmittance to the interior. The influence of layer sequence and ventilation properties on the thermal behaviour was discussed in detail. It is recommended that a spectral optical model combined with a CFD model that includes convection, conduction and radiation is used for analysing and optimising Glass Double Facade (GDF). It was shown that the secondary internal heat transfer factor can be reduced by 2% while total solar energy transmittance values can be reduced by 10% using a well-designed GDF element with free convection.

Other related studies include Hien et al. 2005 [30] study who compared the energy consumption, thermal comfort and condensation between single and double skin facade with TAS and CFD software.

Jiru and Haghighat 2008 [45] used Zonl models to study airflow and temperature in a ventilated DSF. These models are intermediate approach between the extremes of lumped model and CFD. The result revealed that Zonl approach can be employed to provide quick information on the performance of DSF with very minimal computational use.

Hanby et al. 2008 [46] used a dynamic Nodel Network and CFD simulation of a DSF. It was used to enable simultaneous solution of both heat transfer and buoyancy-driven flow within the cavity. The result showed that useful results could be obtained from the Nodel Network approach.

Coussirat et al. 2008 [47] used CFD for modeling flow and heat transfer of DGF. The model involves convection, conduction and radiation heat transfer. The result was compared with experimental data and was validated according to numerical verification and validation procedures.

Cen et al. 2008 [48] used CFD simulation of DSF for thermal analysis reveals the current features inside the thermal channel and the existing problems of double skin facade. Several design models are compared. Finally, the overall heat transfer coefficient and thermal efficiency are calculated. These two key parameters are used for evaluation and design of double skin facades.

Other related studies include Meanwhile, Qin et al. 2009 [49] used Environmental System Performance ESP-r software integrating thermal simulation and air low net work module to assessment the effect of chimney on the DSF.

### 3.5. Shading device and DSF

The main goal in designing a building from an engineer's point of view is to compute the total heat transfer through the cavity. This requires an adequate knowledge of correctly sided inlet and outlet openings, well-positioned shading device, as well as an optimised space between the facade and proper working conditions of fans located in the facade itself [25].

In one experiment, blinds and shading devices were placed inside a cavity between the two skins to provide protection against intrusion, glare and direct sunlight. It is to be noted that external or mid-pane types provide reductions in solar heat gains. In addition, the use of blinds can lead to considerable energy savings if controlled and adjusted correctly [50].

With regards to shading device and DSF, Baldineli 2009 [15] presented the glass double skin facade equipped with integrated movable shading device. Energy performance was determined by measuring the optical properties of materials and by implementing a computational fluid dynamics analysis. Validation was made by comparing with data of similar experimental apparatus. The facade performance was then compared with traditional enclosures such as glazed and opaque walls. The result showed that the facade significantly improves the building energy behaviour, especially when the configuration with winter farced convection is considered. A comparison with opaque walls showed an energy saving of up to 60 kwh per year per facade square meter.

Furthermore, it was found that correct position of the blinds makes it possible to reduce heat consumption of the building. And it was found that light coloured blind tends to invite more light into the office buildings.

Gratia and Herde 2007d [51] illustrated how the position and the colour of blinds affect the cooling consumption in an office building with a double-skin façade wall. They also highlighted the importance of the opening of the double-skin façade. Other interesting factor to note is the impact of the blinds characteristics on human comfort and ergonomics. The result showed that the position and the colour of the blinds have an influence on the temperature of the inner skin windows. Logically and practically, the right setting of blinds can filter the hot radiation coming from the windows to the occupants.

All of this design options are for conventionally located shading devices such as roller shades, louvered blinds, fixed versus manually or automatically controlled, horizontal versus vertical fins, etc. The designer should consider how the device will affect airflow within the cavity, and how solar gains absorbed by the shade will be radiated relative to the interior façade [36]. Furthermore, the types, sizes and positioning of any shading devices depend on the climate and function of buildings. Furthermore, the source of the light may be excluded; whether at a high or a low angle of direct sunlight, diffuse sky light, or perhaps reflected light from the exterior pavement on the street outside [52].

### 3.6. Solar photovoltaic

Double-facades with integrated Photovoltaic (PV) panels may be used to generate electricity, thermal energy, and may also be used for day lighting. Many researchers have examined various configurations of double facades and have developed thermo-fluid models to investigate the performance. However, limited amount of work has been done to develop systematic optimisation procedures to improve their overall performance and cost effectiveness.

Manz 2004 [44] used a spectral optical model and a computational fluid dynamic model to simulate the total solar energy transmittance to the interior. He recommended convection, conduction and radiation for analyzing and optimizing glass double facade. The result showed that total solar energy transmittance can easily vary by a factor greater than five.

Furthermore, Safer et al. 2005 [13] proposed a comprehensive modelling of a compact DSF equipped with Venetian blind and forced ventilation. The model was a three-dimensional airflow. This model involved the CFD approach that determined air movement within the ventilated façade channel. A parametric study was performed to analyse the impact of three parameters on the airflow development. They are the slat tilt angle, the blind position and the outlet position. The result showed that the distance between the blind and the external glazing was found to have a major impact on the velocity inside the DSF channel.

In addition to this, Charron et al. 2006 [36] presented a theoretical study of DF with integrated Photovoltaic (PV) and motorised blinds. PV models were installed in the middle of the cavity. The result showed an increasing PV section overall by about 25% and a decreased electricity generation by 21%.

### 3.7. Glass selection of DSF

Since the last decade, glass has been one of the most important materials in commercial building developments. It has evolved into a high-tech product that can create slender and bold constructions. At the beginning, glass was popularly used as a symbol of an advanced and high class building. The double glazed façade becomes a part of buildings technology and the concern of the owner/developer concerning ecology and energy is transferred visually to the outer shell of the building [28].

Sinclair et al. 2009 [12] proposed that the glazing system design for a DSF depends on the climate conditions of the building site. They preferred ventilation and blind operating models, and stressed on internal space requirements.

In relation to this, Chow and Hung 2006 [53] Chow et al. 2007 [54] claimed that glass facades have the advantage of saving a great amount of energy in winter because these materials reduce both illumination and heating costs by making full use of sun and day light. They also concluded that smaller glass panels would perform better than larger sheets in real constructions. Furthermore, larger temperature difference would occur between the edge and the centre of bigger glass panels. In addition, it was proposed that bigger panels are at greater risk of collapsing. Furthermore, Chow et al. reported that large glass panel would have larger temperature difference between the edge and the centre. The key factor is to select high quality glass samples.

With respect to the selection of glass selection as a wall façade material, Manz et al. 2004 [44] simulated the total solar energy transmittance to the interior of buildings through the glass facade. Spectral optical model and CFD were used. They recommend a spectral optical model combined with a CFD model that includes convection, conduction and radiation for analysing and optimising glass double facade. It was found that the secondary internal heat transfer factor can be reduced by 2% and the total solar energy transmittance values could be reduced by 10% using a well-designed GDF element with free convection.

Perez-Grande et al. 2005 [55] studied the influence of the glass properties on double glazed façades. Ratio of the building was calculated for different glass combinations in double-glaze facades. It was found that an appropriate selection of the glasses forming the channel can reduce the thermal load into the building by almost an order for magnitude.

### 3.8. Smoke and DSF

Extensive use of glass sheets in glazing might cause fire problems. There is a public concern on the safety of buildings that have high window to wall ratio with large glass panels. Experiments with physical scale models were carried out to investigate the fire hazard of DSF. Many new construction projects with DSF failed to comply with the fire safety codes. The temperature gradient inside the glazing could be observed by increasing the risk of thermal that breaks the glaze.

In relation to this, Chow and Hung 2006 [53], Chow et al. 2007 [54], studied the spreading of smoke and flame into the cavity of DSF. The main fire safety concern for DSF is that smoke might spread to other levels through air cavity when a glass panel of DSF is destroyed by fire.

Depth of the cavity was identified as the main agent in fire eruptions in building with DSF. When fire erupts, smoke would move at the centre of the cavity rather than along the wall. Hot smoke will then be forced towards the outer panel at the beginning and bounced back to the inner panel. The upper glass panel would be affected if the hot gas moves upward to the upper inner skin by the induced air flow. Thus, it is suggested that using different types of glass for inner and outer skins might provide more desirable fire safety.

In addition, Ding and Hasemi 2006 [21] examined the possibility of using natural ventilation system of a double-skin façade for smoke control. They conducted reduced-scale model experiments and CFD analysis. It was found that smoke from a fire room escaping through the inner façade into the intermediate space between the two skins may accumulate and spread horizontally or vertically to other rooms that have openings connected to the intermediate space. The result showed that smoke spread can be prevented with suitable arrangement of openings.

### 3.9. Cavity depth of DSF

When considering double skin facades (DSFs), consideration of the cavity that lies sandwiched between the two walls (internal and external wall) is inevitable. According to Sinclair et al. 2009 [12], the depth of the cavity is determined by a number of parameters including the aesthetics, types of shading devices/blinds, access to the cavity for cleaning, and the ventilation strategy that include arrangement and flow rates.

Chen et al. 2009 [2] carried out experiments using a solar chimney model with uniform heat flux on a low wall. The inducing airflow rates were obtained by changing the gap-to-height ratio between 1:15 and 2:5 at different heat fluxes and inclination angles. The optimal gap width or optimal gap-to-height ratio is the gap size or ratio when a maximum ventilation flow rate was achieved. Regardless of the results, the obtained optimal spacing from these studies lack consistency. From heat transfer point of view, the optimal spacing should be the gap size when the vented heat is high, or when the heat is blocked by roof structure.

### 3.10. Wind pressure and DSF

Wind pressure in the one of the most important thing affecting the glass. For DSF it is very important to check for that because DSF have three surfaces subjected to wind pressure due to the airflow between the double facades; those are the outside and inside surfaces of the external skin facade and the outside surfaces of the internal skin facade [56].

According to Grabe 2002 [40], the wind creates differences of pressure that stimulates the airflow in the building. He suggested that values of pressure differences on the façade of the building depend on the direction of the wind, shape and height of the building. In particular, value of the wind pressure coefficient depends first on the direction of wind and for different building construction different formulas are given.

In addition, Luo et al. 2005 [56] studied the wind pressure distribution on each surface of the double-skin facades using wind tunnel tests. Furthermore, the characteristic of the wind pressure distribution on the long-span canopy was also obtained from the tests. Result shown that the effect of wind load is appear when it blowing in front of the canopy and it is almost the same when the wind load acting on the upper and lower surfaces of it.

Other related studies include a study by Zhang et al. 2008 [57] analyzed the wind pressure and gust factor distribution on DSF and comparison of wind load between internal and external facade in different airflow zone by using model tests in wind tunnel and synchronous manometric method on internal and external facades,. Result shown that aroused by vortex shading mostly acts on external facade, while compression force aroused by air-flow adhesion and collision mostly acts on internal facades. And DSF gust factor changes largely as variation of facade's region or wind direction.

Moreover Luo et al. 2009 [58] studied mean wind pressure distribution on DSF used wind tunnel tests. Result shown that mean

wind pressure mostly acts on external facade is larger than that on the internal faced.

On the other hand, to determine the wind load on DSF and predict the load difference between single skin facade and double skin facade Luo et al. 2008 [59] used wind tunnel tests to study the tall building with arc-shape and L-shape double-skin facade. This study indicated that pressure in the draught corridor that acts on the external and internal facade at any point is same. The wind load carried by internal facade can be also decided the same as that of single-skin facade. However the wind load carried by external facade can make a discount when the facade locates at the middle of the arc-shape or the long side of the L-shape corridor, and should be amplified when the facade locates at the end of the arc-shape or the short side and the turning point of L-shape corridor.

Furthermore, in another study done by Luo and Zhang 2009 [60] study the characteristics of the wind loads on the arc DSF with different central angles using wind tunnel tests. Result shown that the wind load of the internal skin facade are even and increase with the central angle decreasing. The wind loads acted in the end of the external skin facade are larger than that on the centre of the external facade and much larger than the single skin facade.

### *3.11. Other impacts*

DSF has other impacts such as optimisation, glare, cost, and durability aspects on the façade. It has been noted that DSF influences the thermal properties of the façade and the maintenance aspects inside the cavity building.

Optimal energy saving requires an appropriate balance of opaque walls and glazing. A double skin façade is one way to manage the interaction between the outdoors and the internal spaces. It also provides some architectural flexibility to the design [55].

Gratia and Herde 2007a, c [5,25], Hoseggen et al. 2008 [32] and Poirazis 2005 [17] believe that energy and productivity savings justify the high cost of DSF. However, this argument must be taken with precaution since the efficiency of DSF does not depend on cost considerations alone. There are many other factors that affect the efficiency of DSF as mentioned earlier.

## 4. Conclusion

The main deductions which can be concluded from the results of the present studies are summarised as follows:

1) The idea of DSF has been a source of numerous studies conducted on different areas since the 1990s.
2) Ventilation is the most important part studied by most of the researchers while the researchers highlights the inadequate past researches done on daylighting.
3) It was found from past researches that shading devices can reduce the external hot gain if it is placed correctly in the DSF cavity.
4) However, it was discovered that DSF pose a high fire hazard risk.
5) The researches done on DSF needs further exploration.
6) Users of the DSF (especially in hot and humid climate) are still in the early stages of development. Therefore, urgent theoretical and experimental research works is needed in order to clearly understand the challenges, effects and implications of DSF.

In conclusion, double skin facade (DSF) has been proven to be highly useful and significant in current building developments. The only downside of double skin facade is that it is said to be more expensive than the traditional single glass façade. However, it is widely agreed by many experts that double skin facade (DSF) is more cost-effective in the long run. This is because it is long lasting and more durable as compared to the single glass façade. In addition, it provides other benefits that cannot be found in single glass facade. One of it is that double skin facade helps create a more comfortable and eco-friendly office environment which in turn, further reduces maintenance costs as it saves the building's energy resources.

Finally, DSF systems have great potential for decrease energy consumption in wide ranges of research areas. The systems based on the ideal can find significant opportunities to be used in some innovative and prospective studies with multidisciplinary research structure.

Thus, the researchers of this study propose future works and more studies to be done on DSF designs, on the problems in DSF designs and its impact on the environment, building ergonomics and human psychology, and comfort. Innovations in DSF designs should be further pursued and DSF applications in buildings should seriously be considered as an element in addressing climatic changes and environmental hazards as it is cost and energy efficient.

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